US007893745B2

(12) **United States Patent**
Al-Shahrani

(10) **Patent No.: US 7,893,745 B2**
(45) **Date of Patent: Feb. 22, 2011**

(54) **WIDEBAND PROGRAMMABLE PHASE SHIFTING CIRCUIT**

(75) Inventor: **Saad Mohammad Al-Shahrani**, Dhahran (SA)

(73) Assignee: **King Fahd University of Petroleum and Minerals**, Dhahran (SA)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 66 days.

(21) Appl. No.: **12/458,029**

(22) Filed: **Jun. 29, 2009**

(65) **Prior Publication Data**

US 2010/0327931 A1 Dec. 30, 2010

(51) **Int. Cl.**
H03H 11/16 (2006.01)

(52) **U.S. Cl.** **327/231**; 327/237; 327/246

(58) **Field of Classification Search** .... None
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,985,905 A	1/1991	Kubinec	
5,399,995 A	3/1995	Kardontchik et al.	
5,589,793 A *	12/1996	Kassapian	327/536
RE35,829 E	6/1998	Sanderford, Jr. et al.	
RE37,452 E	11/2001	Donnelly et al.	
6,313,707 B1	11/2001	Fischer et al.	
6,317,006 B1	11/2001	Welland et al.	
6,535,071 B2	3/2003	Forbes	
6,901,126 B1	5/2005	Gu	
7,109,765 B1	9/2006	Wang et al.	
2001/0024139 A1*	9/2001	Yasue	327/536
2008/0122491 A1*	5/2008	Kuan	327/43
2009/0015340 A1	1/2009	Dally et al.	

FOREIGN PATENT DOCUMENTS

WO	WO2007073150 A1	6/2007
WO	WO2008018769 A1	2/2008

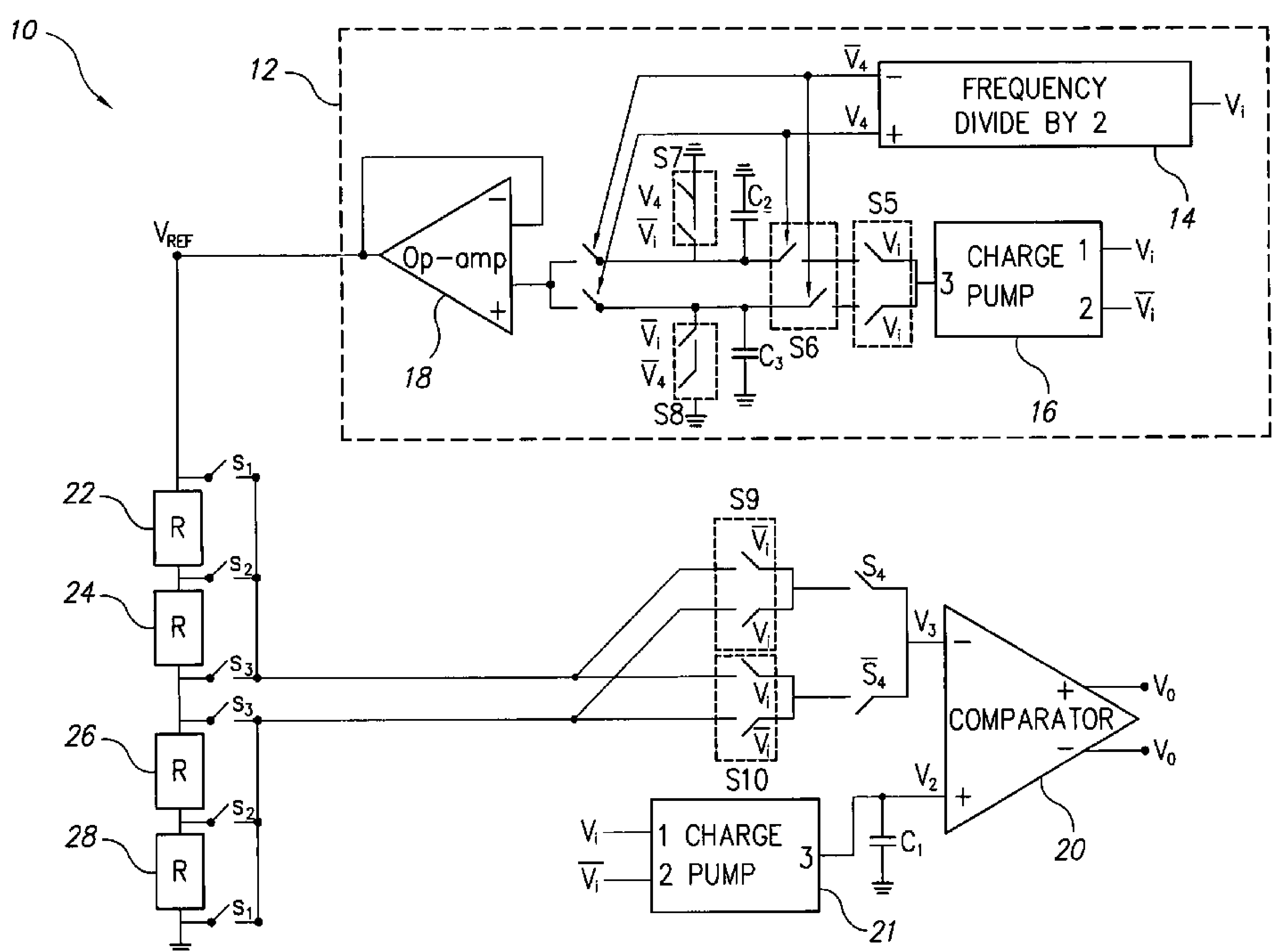
* cited by examiner

Primary Examiner—Tuan Lam
(74) *Attorney, Agent, or Firm*—Richard C. Litman

(57) **ABSTRACT**

The wideband programmable phase shifting circuitry includes a charge pump, a comparator, and a voltage reference generator block. An input signal controls the charge pump which charges and discharges a capacitor connected to an output of the charge pump. The comparator continuously compares the voltage across the capacitor with a reference voltage, ratio of V_{REF}, which is generated by the voltage reference generator block. The voltage V_{REF} is generated to compensate for power supply and integration process variations. The voltage reference generator is comprised of a charge pump unit, a frequency divider unit, switches, and two capacitors. The adjusted V_{REF} ratio controls the comparator threshold level and hence a programmable phase difference between the input signal of the charge pump and the output signal of the comparator.

7 Claims, 6 Drawing Sheets



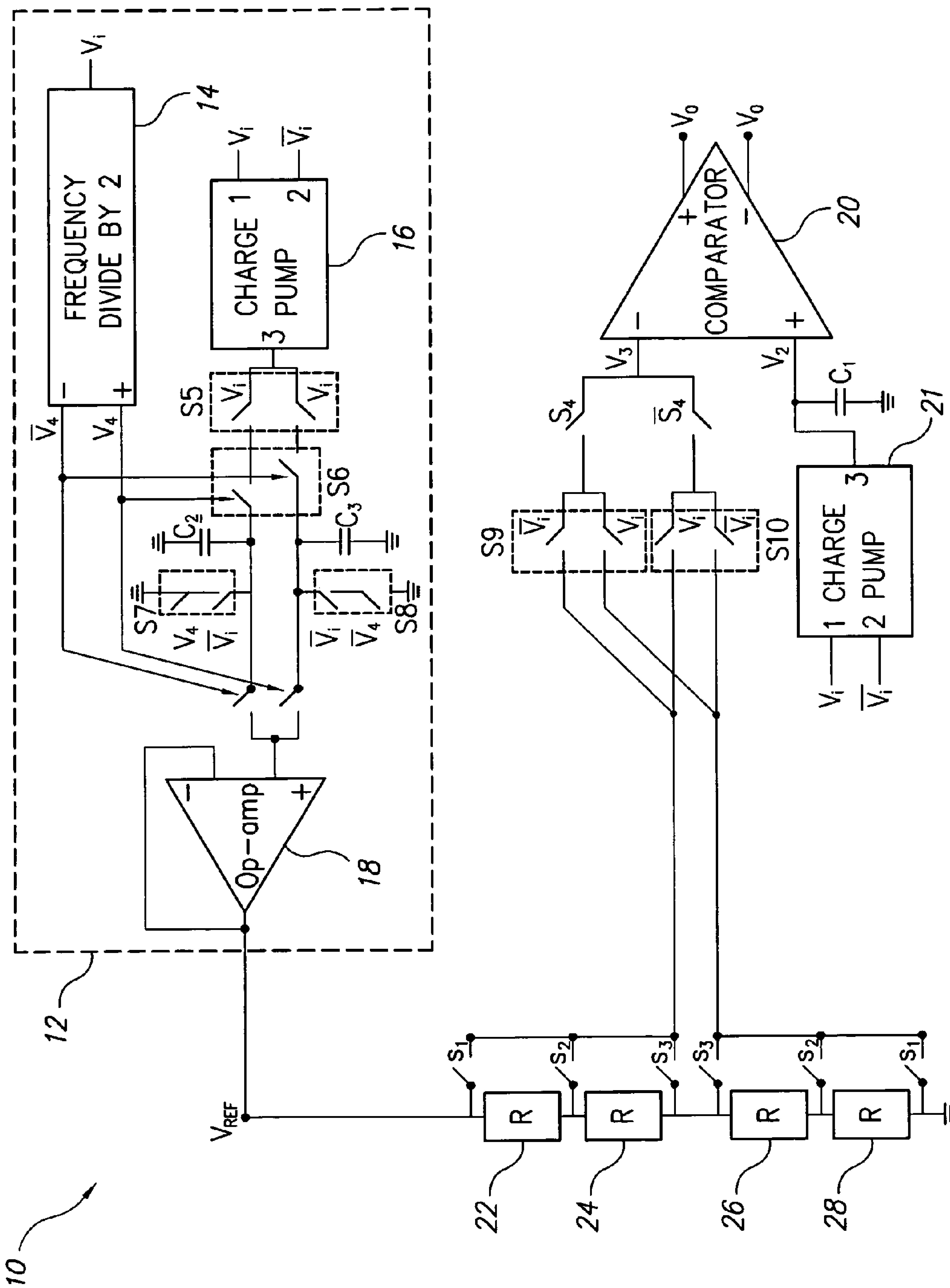

FREQUENCY DIVIDE BY 2
14
CHARGE PUMP
1
2
3
16
S5
S6
S7
S8
C_2
C_3
Op-amp
18
12
V_{REF}
10
COMPARATOR
20
V_o
V_3
V_2
C_1
21
S9
S10
CHARGE PUMP
S_1
S_2
S_3
S_4
R
22
24
26
28

Fig. 1

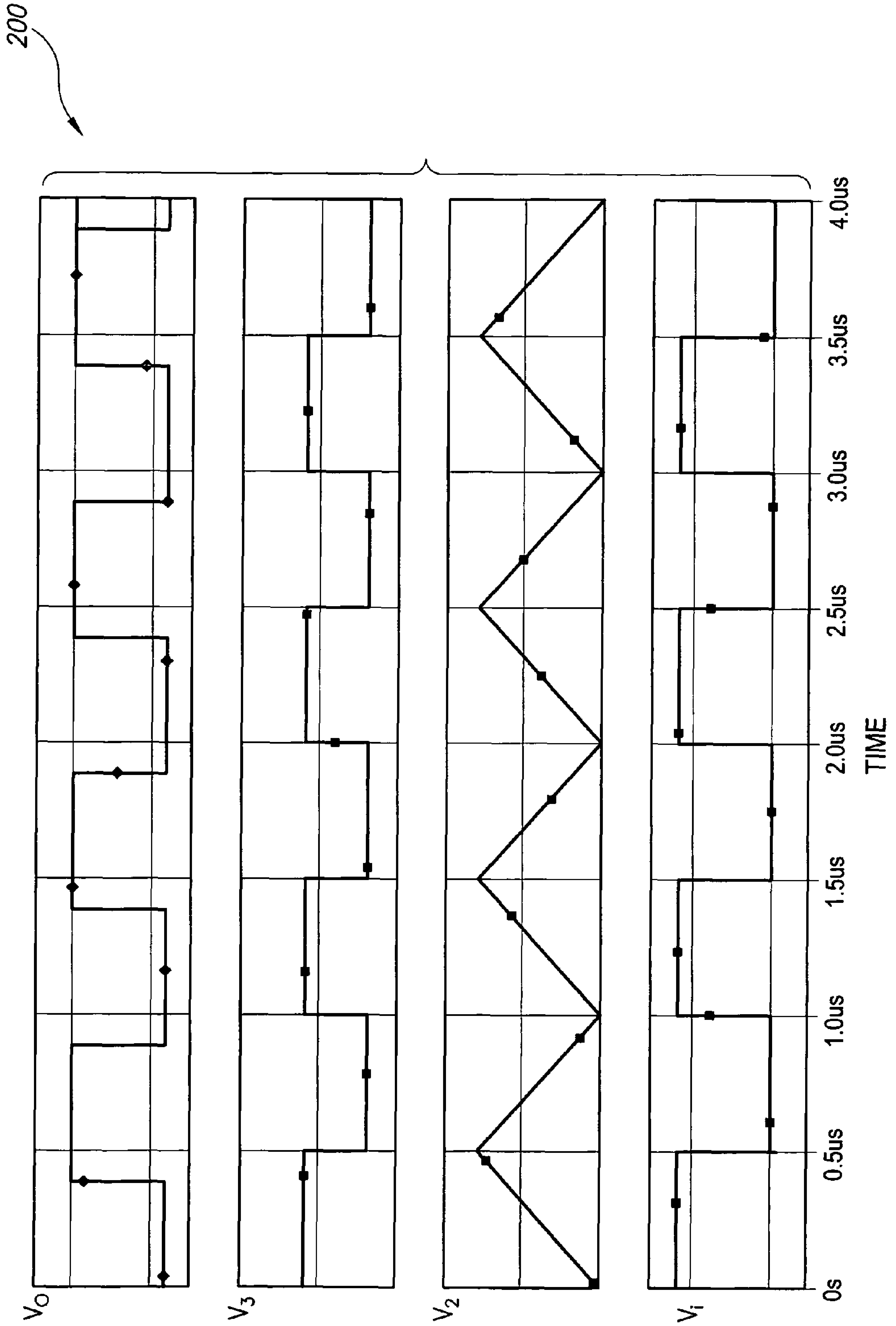


Fig. 2

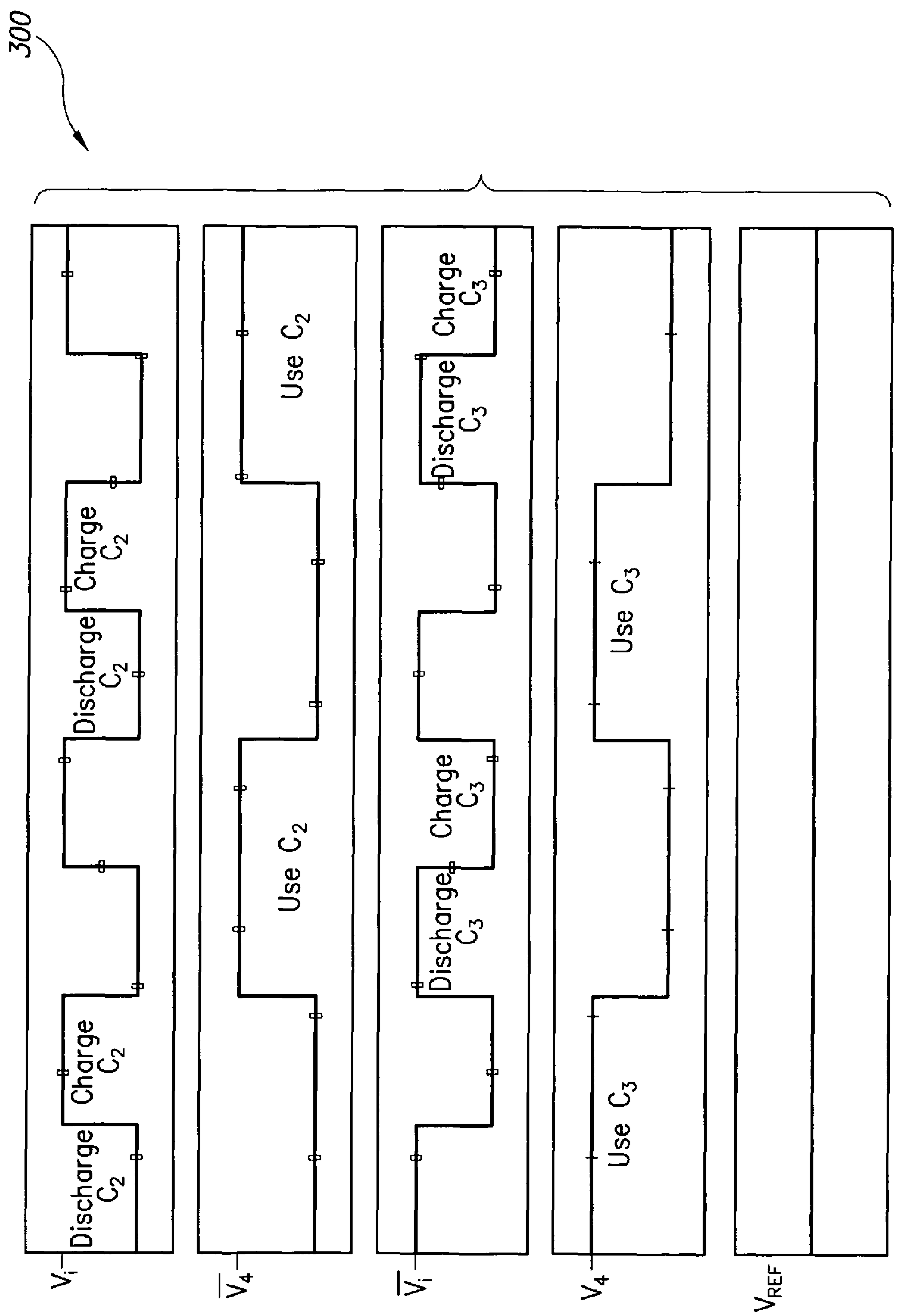

300
Discharge C2
Charge C2
Discharge C2
Charge C2
Use C2
Use C2
Discharge C3
Charge C3
Discharge C3
Charge C3
Use C3
Use C3
Vi
V4
Vi
V4
VREF

Fig. 3

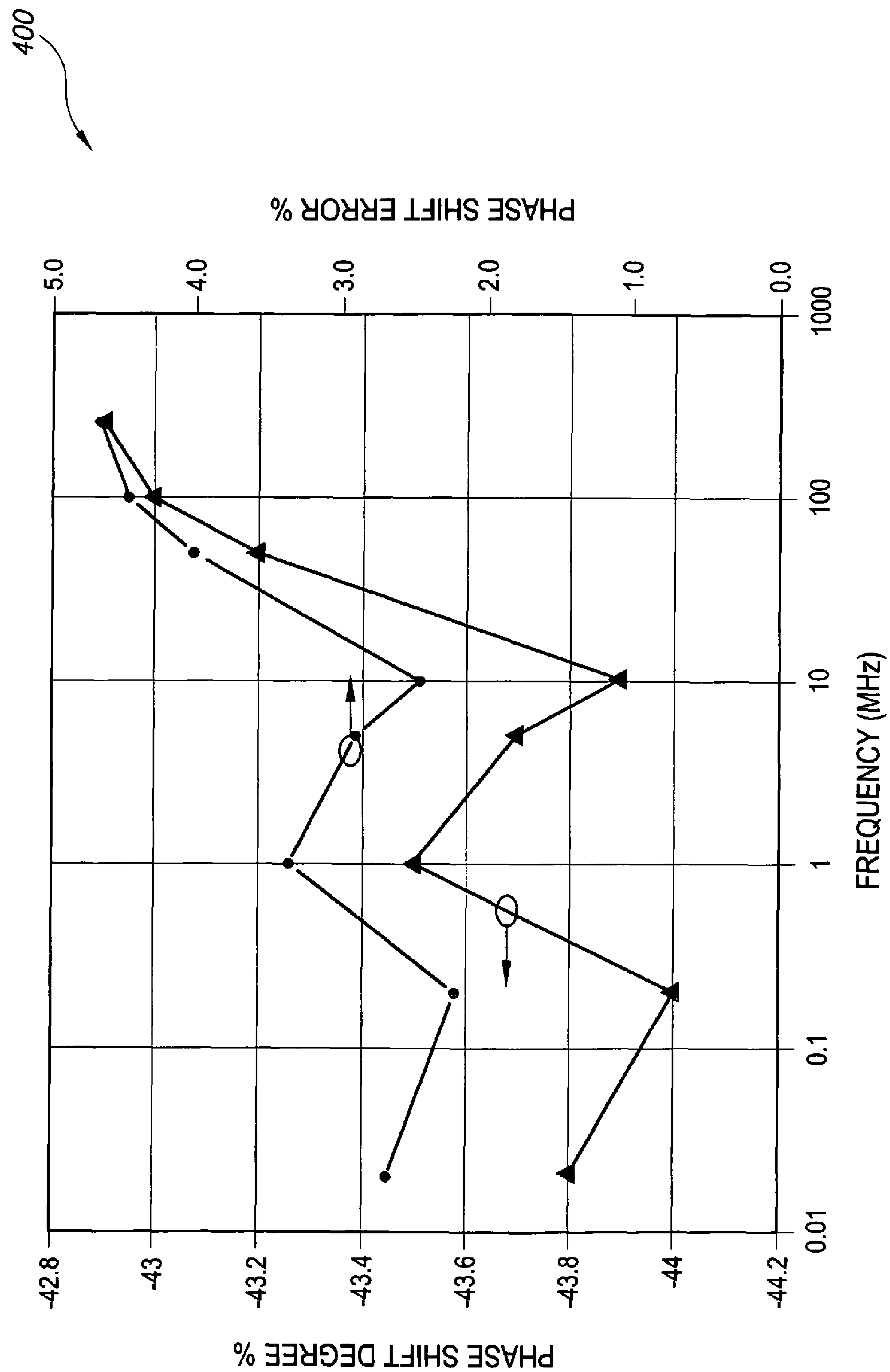
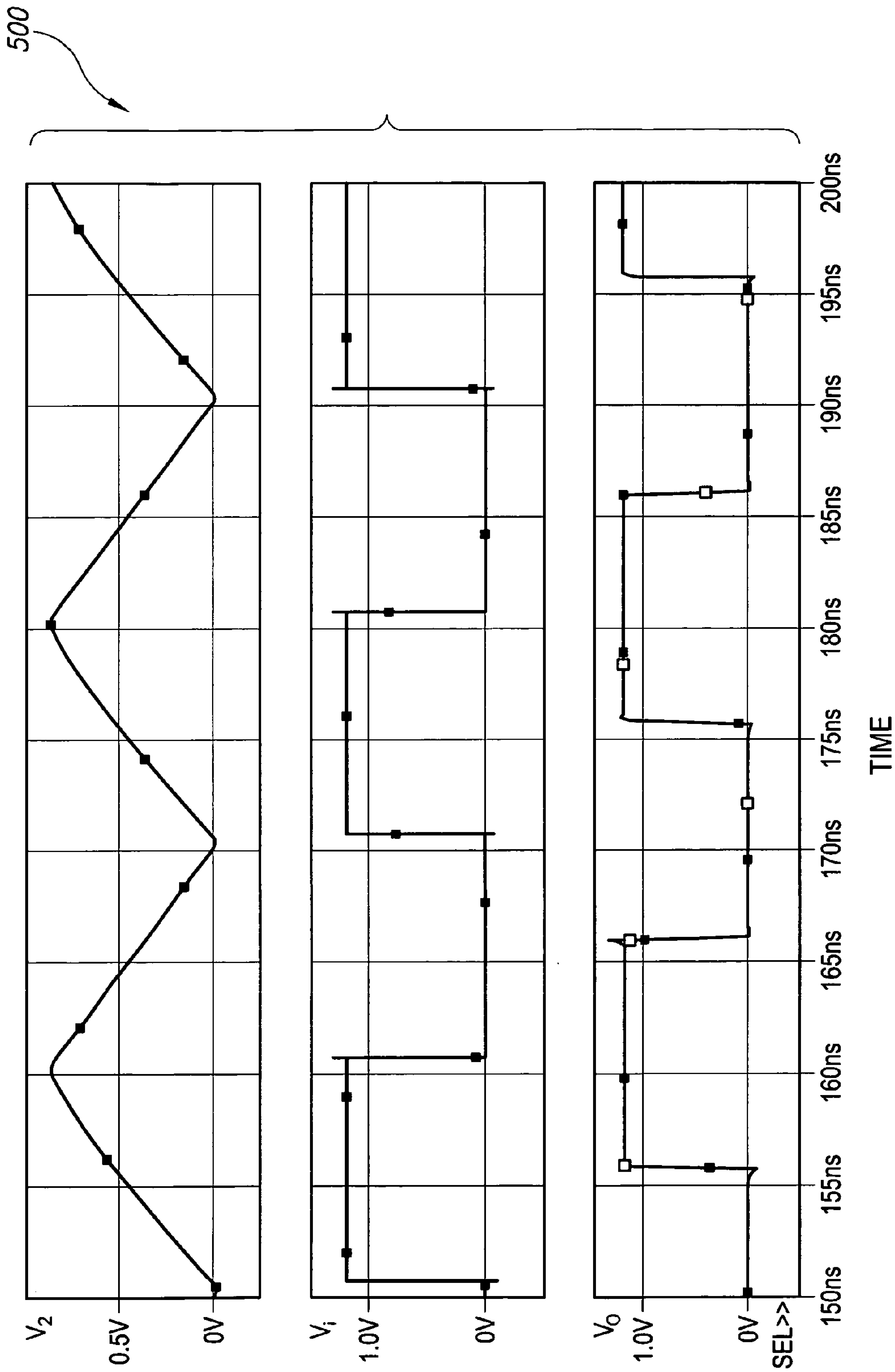

400
PHASE SHIFT ERROR %
5.0
4.0
3.0
2.0
1.0
0.0
PHASE SHIFT DEGREE %
-42.8
-43
-43.2
-43.4
-43.6
-43.8
-44
-44.2
FREQUENCY (MHz)
0.01
0.1
1
10
100
1000

Fig. 4



500
V_2
0.5V
0V
V_i
1.0V
0V
V_O
1.0V
0V
SEL>>
150ns
155ns
160ns
165ns
170ns
175ns
180ns
185ns
190ns
195ns
200ns
TIME

Fig. 5

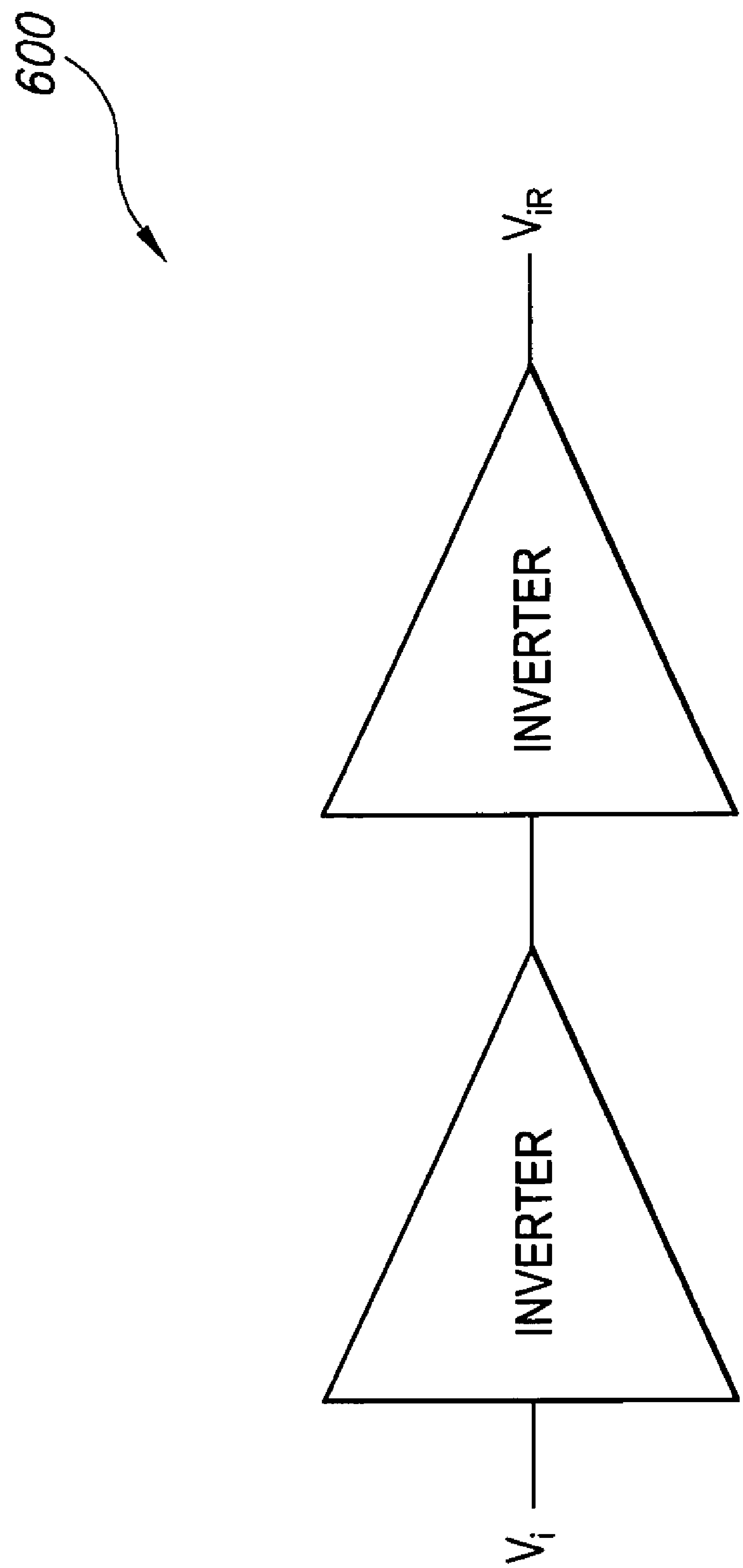


Fig. 6

WIDEBAND PROGRAMMABLE PHASE SHIFTING CIRCUIT

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates generally to phase shifting circuitry. More specifically, the present invention relates to a phase shifter that can be adjusted digitally, precisely, and independently of process and supply variations.

2. Description of the Related Art

A phase shifter circuit can find wide applications in instrumentation, measurement, communication, and control systems. The literature shows different types of phase shifters, which include frequency-dependent, frequency-independent, and auto-tuning phase shifters. The frequency-dependent phase shifter circuit provides fixed or variable phase shift at a single frequency. On the other hand, a frequency independent phase shifter provides a fixed phase shift over a wide range of frequency. Auto-tuning phase shifter's main application is related to phase calibration. Automatic phase shifters may be used in a transceiver system to compensate phase mismatching. Vector modulation is one of the common realizations for phase shifters, wherein a variable phase shift may be obtained by adding the outputs of multiphase filters having adjustable amplitudes. However, such a scheme disadvantageously introduces a stringent requirement for a wide range and accurate controllability of the output amplitude of a large number of filters. While numerous other phase shift designs are known, none taken either singly or in combination, are seen to describe the instant invention as claimed.

Thus, a wideband programmable phase shifting circuit solving the aforementioned problems is desired.

SUMMARY OF THE INVENTION

The wideband programmable phase shifting circuit includes a charge pump, a first comparator, and a voltage reference generator block. The input signal controls the charge pump which charges and discharges a capacitor coupled to an output of the charge pump. The comparator continuously compares the voltage across the capacitor with a reference voltage, ratio of V_{REF}, which is generated by the voltage reference generator block. The voltage V_{REF} is generated to compensate for the expected power supply and integration process variations.

The voltage reference generator block is comprised of a second charge pump, a frequency divider unit, a plurality of switches, and two capacitors. The adjusted V_{REF} ratio controls the comparator threshold level and hence the phase difference between the input signal of the charge pump and the output signal of the comparator.

A CMOS implementation for the invented phase shifting circuit is presented which provides a wide phase shifting over five decades of frequency, 2 KHz-250 MHz, with a minimal phase error, less than 4.7%.

The phase shift circuit can be implemented as an integrated circuit, and can be operated with a power supply delivering as little as 1.2 volts. The number of different phase shifts generated by the inventive circuitry is limited only by the number of resistors at the comparator input.

These and other features of the present invention will become readily apparent upon further review of the following specification and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** shows a schematic diagram of a wideband programmable phase shifting circuit according to the present invention.

FIG. **2** is a plot showing the waveforms at different nodes produced by a wideband programmable phase shifting circuit according to the present invention.

FIG. **3** is a plot showing the waveforms at different nodes of the V_{REF} generator circuit of a wideband programmable phase shifting circuit according to the present invention.

FIG. **4** is a chart showing the performance of the CMOS phase shift circuit over a wide band of frequencies in a wideband programmable phase shifting circuit according to the present invention.

FIG. **5** are plots showing the voltage waveforms of the CMOS phase shift circuit when adjusted to provide a 45° phase shift in a wideband programmable phase shifting circuit according to the present invention.

FIG. **6** is a partial schematic diagram showing two inverters in cascade to generate a new reference input signal in a wideband programmable phase shifting circuit according to the present invention.

Similar reference characters denote corresponding features consistently throughout the attached drawings.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

As shown in FIG. **1**, the wideband programmable phase shifting circuitry **10** is comprised of a first charge pump **21**, which charges a capacitor C_1 as a V_2 reference input to a comparator **20**. A voltage reference generator block **12** provides a reference voltage V_{REF} as input to a chain of resistors in series comprised of resistances **22**, **24**, **26**, and **28**. Input voltage V_i controls charge pump **21**, which charges and alternately, discharges capacitor C_1, which is coupled to the output of charge pump **21**.

The comparator **20** continuously compares the voltage across capacitor C_1 with a voltage dependent upon the reference voltage V_{REF}, said reference voltage V_{REF} being generated by the voltage reference generator block **12**. Charge pump **21** has input pin **1** connected to the input signal V_i and input pin **2** connected to complement input signal $\overline{V}i$ respectively. To demonstrate the operation of the inventive wideband programmable phase shifting circuitry, consider the following scenario. With V_i high (1.2V), output pin **3** of charge pump **21** charges the capacitor C_1 with a constant current.

As shown in plot **200** of FIG. **2**, the voltage V_i provided at input pin **1** of charge pump **21** is a square wave voltage which swings between a nominal low value and a nominal high value. The charging that occurs at capacitor C_1 is repeated every high half cycle, i.e., when V_i is high. In the other half cycle, low V_i, charge pump unit **1** draws a constant current I_1 from the capacitor C_1, so that both halves combine to form an integration of the square wave input V_i, hence a triangular waveform signal V_2 (as shown in FIG. **2**) is generated across capacitor C_1.

The comparator **21** compares signals V_2 and V_3 and provides high output signal, V_o, if V_2 exceeds V_3 and low V_o if V_2 is smaller than V_3. As a result, the comparator **21** generates an output signal V_o having substantially the same waveform of input signal V_i but at a predetermined phase ϕ difference from the input signal V_i. The switches S_1-S_4 are used to adjust the voltage level V_3, thereby controlling the phase shift ϕ of output signal voltage V_o from input signal voltage V_i. The comparator **21** also provides the complement of V_o at its minus output terminal.

To illustrate the process in further detail, the voltage waveforms at different nodes of FIG. **1** are presented in FIG. **2**. Consider the case when switch S_2 and S_4 are on, hence V_3 will be set to ¾ of the reference voltage V_{REF} when the input signal V_i is high and will be set to ¼ V_{REF} when V_i is low. Thus the phase shift ϕ can be described by equation (1).

$$\phi = \frac{180^\circ C_1 k V_{REF}}{\frac{T I_1}{2}} \tag{1}$$

where k is the reference voltage ratio.

The voltage V_{REF} is generated using the reference voltage generator **12**. The voltage V_{REF} is generated to compensate for expected power supply and integration process fluctuations. The voltage reference generator is comprised of a second charge pump **16** connected via switch blocks S_5 and S_6, to capacitors C_2 and C_3. A frequency divider **14** has its outputs V_4 and $\overline{V}_4$ connected to the same switch blocks S_5 and S_6. Switch blocks S_5 and S_6 control the amount of charge that can be pumped into capacitors C_2 and C_3 and thus the magnitude of the voltage V_{REF}. Switch blocks S_7 and S_8 control the discharging process of the voltages of capacitors C_2 and C_3, and thus the voltage V_{REF} values will be frequent updated. The operational amplifier **18** has a unity gain configuration which is inserted as a buffer to provide the capacitors C_2 and C_3 voltages with good driving capability.

The voltage waveforms shown in plot **300** of FIG. **3** depict the charging, discharging, and utilization period of the voltages across C_2 and C_3. V_{REF} can be obtained by equation (2).

$$V_{REF} = \frac{I_1 T}{2C}, \text{ where } C_2 = C_3 = C \tag{2}$$

From equations (1) and (2), and with C_1=C, the phase shift ϕ can be given by:

$$\phi = 180^\circ \text{ k} \tag{3}$$

As depicted from equation (3), the phase shift ϕ is independent of process and supply variations. Moreover, the phase shift value can be selected precisely through a digital word of four bits b_1-b_4, which controls the switches S_1-S_4. The chain of equal resistors **22**, **24**, **26**, and **28** in conjunction with the switches S_1-S_4 is used to provide four different voltage levels for V_3. Consequently seven different phase shifts values, (−45°, −90°, −135°, 45°, 90°, 135°, and 180°), are obtained. More values of phase shift, i.e., a finer resolution, can be obtained by including more resistors in the chain.

Although the phase shifting circuitry of FIG. **1** can be implemented in different technology processes, it has been implemented here as an example in a 0.18 μm CMOS technology to prove functionality and performance of the inventive wideband programmable phase shifting circuitry. The obtained result shows a good agreement between the theoretical and simulated results over wide ranges of phase shift and frequency.

The phase shift error plot **400** shown in FIG. **4** reveals that an error less than 4.7% is obtained over the frequency band of 2 KHz-250 MHz. Plot **500** of FIG. **5** shows the waveforms of V_2, V_i, and V_o at input frequency of 50 MHz and a phase shift of 90°.

In the embodiment shown, the comparator delay is found to be 45 ps, which is a negligible amount of delay for a frequency operation lower than 50 MHz. However, the comparator delay of 45 ps represents a major source for phase shift error in the higher operating frequency range. As shown in FIG. **6**, a cascade **600** comprising two CMOS inverters can be used to generate a new reference input signal which is compared with the output signal of the phase shifting circuit, thereby overcoming the comparator delay problem.

In summary, the adjusted V_{REF} ratio controls the comparator threshold level and hence the phase shift difference between the input signal of the charge pump and the output signal of the comparator. A CMOS implementation for the invented phase shifting circuit is presented which provides a wide phase shifting over five decades of frequency, 2 KHz-250 MHz, with a minimal phase error, less than 4.7%.

It is to be understood that the present invention is not limited to the embodiment described above, but encompasses any and all embodiments within the scope of the following claims.

I claim:

1. A wideband programmable phase shifting circuit, comprising:

a divide-by-two frequency divider having an input accepting a periodic input signal voltage and having an output that generates a signal having twice the period of the periodic input signal voltage;

an amplifier having at least one input connected to the output of the frequency divider, the amplifier generating a reference voltage output;

a reference voltage generator charge pump having inputs accepting the periodic input signal voltage and a complement of the periodic input signal voltage, an output of the reference voltage generator charge pump being connected to the at least one input of said amplifier;

a comparator having a first input, a second input, and at least one output;

a switched voltage divider network connected to the reference voltage output of the amplifier, the switched voltage divider network having an output generating a percentage of the reference voltage, the reference voltage percentage being determined by a switch configuration of the switched voltage divider network, the switched voltage divider network output being connected to the first input of the comparator; and

a comparator charge pump having inputs accepting the periodic input signal voltage and a complement of the periodic input signal voltage, an output of the comparator charge pump being connected to the second input of the comparator;

wherein the at least one output of the comparator generates a periodic output signal voltage having a phase shift with respect to the periodic input signal voltage, a value of the phase shift being determined by the reference voltage percentage applied to the first input of the comparator.

2. The wideband programmable phase shifting circuit according to claim **1**, wherein the amplifier is an operational amplifier.

3. The wideband programmable phase shifting circuit according to claim **2**, wherein the operational amplifier is configured for unity gain closed loop operation.

4. The wideband programmable phase shifting circuit according to claim **1**, further comprising means for precisely setting the phase shift of the output signal with respect to the input signal.

5. The wideband programmable phase shifting circuit according to claim **4**, further comprising means for providing an arbitrarily large number of phase shift settings of the output signal.

6. The wideband programmable phase shifting circuit according to claim **1**, wherein the phase shift circuit is implemented in an integrated circuit having properties optimized for low power consumption.

7. The wideband programmable phase shifting circuit according to claim **1**, wherein the phase shift circuit is implemented in an integrated circuit having properties optimized for high speed operation.

* * * * *